Carbon Footprint Reduction During the Wire Drawing Process at an Electrical Cable Manufacturing Company

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Abstract

This study proposes improvements in one of the processes of the operational flow of an electric cable manufacturing company with the objective of reducing the environmental impact of its emissions. The improvement focuses on the copper annealing sub-process, in relation to the wire drawing operation. Under an experimental design, a diagnosis was made of the 2.5 mm diameter wire production process. It was found that it generated unnecessary waste of electrical energy in the annealing stage. With the help of a group of experts, the carbon footprint indicator was also calculated. The solution implemented consisted of the partial elimination of the primary drawing annealing operation and recurring adjustments for the efficient operation of the rest of the process. The benefit of the proposal, validated through laboratory tests, was calculated at USD 2.81 per year for each dollar invested. The results show that the wires only changed in their mechanical properties, having mainly an elongation of 35%-36% for the soft wire and 2% for the hard wire. However, the change in these mechanical properties does not chemically affect the quality of the final product thanks to the adjustments made, reducing the carbon footprint by 1444,186 tCO2 per year. This proposal could be replicated in similar companies in the metallurgical sector.

Keywords
Carbon footprint, wire drawing, annealing, electric cables.

1. Introduction
Climate change has been present as a process related to a group of manifestations over time causing a variation in the parameters established for the climate during annual temperature periods, precipitations and atmospheric movements (Cordova, 2020). This climate variation is mainly produced by Greenhouse Gas Emissions (GHGs) as a result of the inefficient use of natural resources. This is causing manufacturing companies to actively seek solutions regarding these types of gasses emissions, misuse of electrical energy and resources within industrial processes.

In the past years, tools have been developed for GHGs management, one of them being the carbon footprint associated with organizations, permitting the quantification of these directly or indirectly generated emissions by the company's activities (Nuñez, 2012). This tool has been progressively gaining relevance due to clients' demand, and as well as the legislative authority, since some countries have started establishing laws concerning the calculation of this, also known as, indicator (Hoyuelos et al., 2020).

In a survey that took place in 2020 to several consumers from various countries, it was revealed that approximately two thirds of them supported the inclusion of the Carbon Footprint labeling of their products. The reason being that a significant number of them are aware of climate change and they'd rather buy products from companies committed to reducing their environmental impact (Vilda, 2020). In consequence, this has affected the perception companies, as well as their stakeholders have related to the added value to their products along with their mission towards the environment.

Regarding the economy of these companies, despite the economic difficulties they faced in 2019, an estimation was obtained to expand the opportunities for their improvement. It should be pointed out that this growth estimate requires some regulatory changes to be applied this year, such as in infrastructure. If no changes were applied and a low rate in investments is repeated, the expansion would range between 2.5% and 2.9% (SNI, 2020). Therefore, the issue that was addressed during this investigation was focused on electrical power over expenses reduction from companies within certain processes, which can be expressed as environmental impact through the carbon footprint.

Even when the calculation of this indicator for peruvian companies already exists, we find a lack of information related to the industrial sector, specifically in the production area where the added value chain for the end product is an essential subject. The purpose of this investigation was to develop and apply engineering tools for analysis, evaluation and proposal of an improvement for the environmental impact reduction, applied during the wire drawing process.

1.1 Problem Diagnosis

Initially, for the problem analysis, the most sold wire drawing process was described:
The wire drawing process consists in reducing the diameter of the copper wire without using heat. The copper wire is stretched using rows and drawing dies made of polycrystalline diamond, where the copper wire passes through until the desired diameter is met. This operation is constituted by the following four stages:

The first stage of the wire drawing process is known as Primary wire drawing. It began with the reception of the raw material, in this case copper wire stored in large coils. The wire entered the two-wire drawing machine with an initial diameter of 8mm and it was reduced to 2.05 - 2.58 mm. This machine works using AC power and utilizes motor-driven pulleys to pull the wire through the drawing dies. During this process, the material lost its mechanical properties and a harder wire was obtained.

It is required this wire to be soft and malleable solely in order to be stored in metallic baskets or Coilers before being able to go through the wire drawing process a second time employing a second wire drawing machine to continue reducing its diameter. For this, the wire needed to have recovered its mechanical properties previously lost. This was obtained through the Initial annealing sub process.

The initial annealing sub process consists in dragging the hard copper wire, obtained after the Primary wire drawing process, along an arrangement of pulleys that make the wire run through two cathodes that constantly apply voltage to the running wire, heating it and making it recover its malleability properties. To prevent the corrosion of the copper wire while being heated, an inert atmosphere chamber containing nitrogen was included in between the cathodes. After exiting the chamber, the heated copper wire goes through a cooling process utilizing an oil and water emulsion acting, not only as coolant, but as well as keeping the system unpolluted and lubricant.

It should also be mentioned that each wire drawing machine has its own annealing line incorporated, as well as an oil and water emulsion intake administered in different concentrations, depending on the sub process to be applied.

The second stage was the Secondary wire drawing taking place in the intermediate wire drawing machine 8. The 2.05 - 2.58 copper wire entered the intermediate wire drawing machine to obtain thinner wires ranging between 0.65 - 0.715 mm of diameter (Figure 1).

This, again passed through an annealing process similar to the Initial one, in order to recover its malleability, once again, lost during the Secondary wire drawing process. This will get the copper wire ready for further steps.

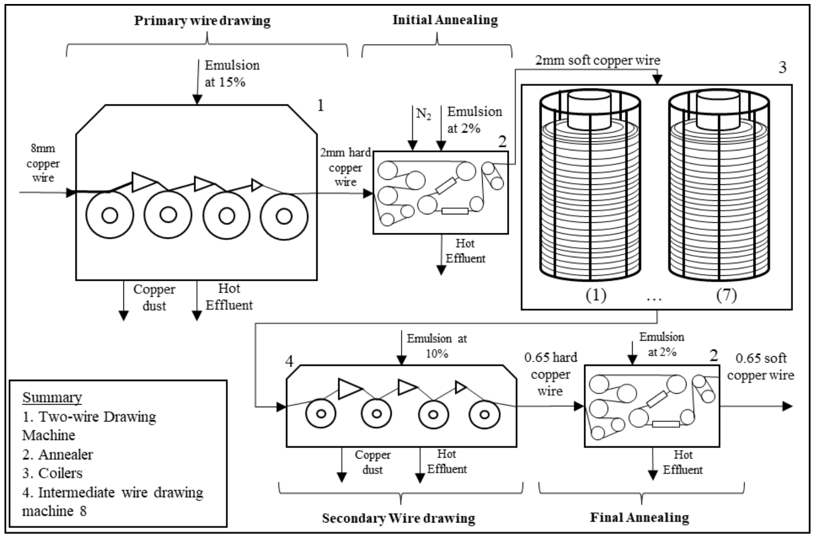

Figure 1. Drawing process flow diagram

Environmental impacts were detected within this process such as soil, water and air contamination, however, these are controlled by recycling programs, effluent treatment and mitigation by extractors, accordingly. Nonetheless, it was found that during the Initial annealing process, excessive electrical power could have been used. This problem was detected using the following Ishikawa diagram (Figure 2):

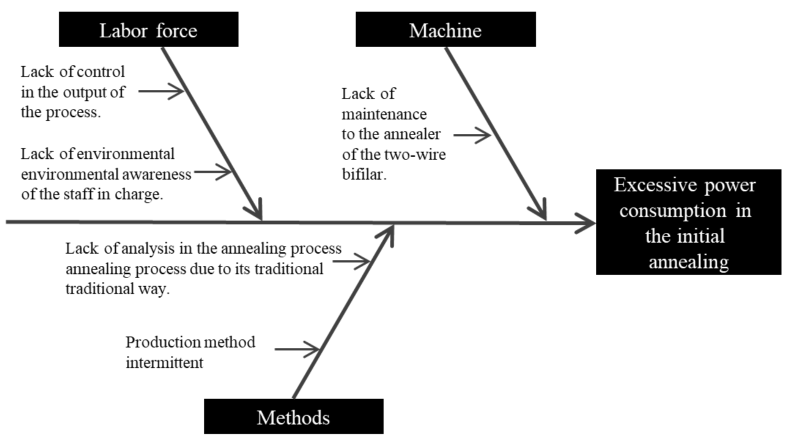

Figure 2. Ishikawa Diagram

This diagram shows that human error was the main cause for the over consumption of electrical power, due to the lack of control from the Quality department and the operator’s unawareness about the environmental impact of the task, machinery failures due to the lack of maintenance.

Furthermore, the annual electrical power consumption was calculated in order to show the cost of this operation utilizing the three-phase current formula: ($\sqrt{3}$*V*A)/1000. This power was calculated on the cathodes in the annealing process (Table 1).

Table 1. Calculation of the annual electricity consumption in the initial annealing process

Detail	2.05 mm diameter wire	2.58 mm diameter wire
Machine speed (m/s)	15	16
Stroke voltage (V)	46,5	53,8
Stroke amperage (A)	5961	6510
Factor (√*3)*	1,732	1,732
Power (kW)	480,09	606,61
1 coiller capacity (m)	50000	35000
Time to fill 1 coiller (h)	0,926	0,608
Energy consumption per coiller (kWh)	444,53	368.6
Monthly production (coillers)	150	350
Monthly power consumption (kWh)	66678,75	129010,41
Total annual power consumption (kWh)	2348269,96	

Is, in this manner, that the annual electric power consumed during the first stage of the wire drawing process was of 2'348,269.96 kWh. This represents a significant power consumed during this stage. The emissions were calculated utilizing the Carbon footprint formula:
Carbon footprint (t CO2 eq) = electric power (kWh) x emission factor (kg CO2/kWh) x 1t/1000kg
In accordance with the Kioto Protocol it was obtained that the emission factor for electrical power is: 0,615 kg CO2 for each kWh (Table 2).

Table 2. Annual carbon footprint calculation

Annual electric energy consumption (kWh)	Emission factor (kg CO_2/kWh)	Annual carbon footprint (t $CO_{2\ eq}$)
2348269,96	0,615	1444,186

The carbon footprint obtained represents the quantity of CO2 produced by the initial annealing, which was interpreted according to the company's approach to its GHGs emissions and their control.

2. Literature Review

The carbon footprint of products is playing an increasingly important role in the sustainability decisions of companies and consumers. Its study and application contribute to mitigating climate change by reducing it in different stages of the production process (Meinrenken, 2022). Likewise, the increase in the production, storage and consumption of goods stipulated by globalization has caused this problem, triggered by the generation of GHGs, to become relevant in recent years. Some authors argue that the analysis of the supply chain, within industries, offers an important opportunity for the reduction of emissions through the development of optimization models for its subsequent configuration (Robles-Amando, 2017).

Similarly, the Sustainable Development Goal underscores the urgency of ensuring a sustainable supply chain with novel technologies including, for example, Artificial Intelligence to decrease food loss, which has the potential to mitigate food waste. In this article, the author focused on paradigm shifts from traditional manufacturing to automated industrial practices especially in different parts of the supply chain within a food processing company. These technologies increased their productivity especially in perishable products thus improving accuracy, speeding up processes, reducing costs and mainly the carbon footprint of food (Amani,2022).

On the other hand, some authors argue that, thanks to the implementation of process simulation models, energy, material or economic savings can be achieved. In an industrial aluminum extrusion plant, accumulated energy demand models were applied from start to finish, and improvements were identified and adapted to the process. These improvements were able to reduce energy and material costs while avoiding the release of CO2 into the environment (Oberhausen et al., 2022). In the same way, a study of Electrical Energy Saving in Orcopampa mining was carried out, which helped to detect some operating conditions of the system. Based on the results of this study, a program of energy saving actions was developed and implemented continuously and independently. The results of the application of this program had beneficial results for the company, in terms of saving energy, money and reducing the carbon footprint (Hinostroza, 1995).

In other articles, the simulation of the proposals for the standardized industry was carried out. On one hand, Pajares (2013), notes that by applying modern techniques of prediction and simulation will optimize the use of electricity within an industrial plant in general.

In addition, Sandoval (1993), argues that, facing a situation of energy crisis, a policy of rational use of energy resources is necessary, through actions oriented to reducing specific energy consumption. The research presented a flowchart that summarizes the steps that must be taken with each of the industries to achieve energy savings, which translates into the reduction of the carbon footprint.

On the other hand, all companies in the productive sector are large consumers of electricity, which represents a large part of their production costs. Globalization requires large corporations to be more competitive not only economically but also in a sustainable way. For this reason, a bakery company conducted a study on the improvement of the Qualification Factor, reviewed the production process, the continuous and floating programming line, as well as the consumption and demand of electric energy. This resulted in the reduction of electric energy costs and carbon footprint (Mandujano, 2006). In addition, strategies were proposed based on these results to continue with the task of reducing the carbon footprint in this industry (Huang, 2022).

The national industry has an urgent need to reduce its operating costs in a sustainable manner in order to face the international market from the best competitive positions. The need to optimize processes in order to improve product quality is strongly linked to the cost of electricity and sustainable development. In the electric cable industry, a Program for the Optimization of the use of electric energy was carried out involving all the company's personnel. It was possible to reduce energy consumption and, therefore, also the carbon footprint through plant modernization, process automation, loss control and proper energy management and maximum electricity demand (Sotelo, 2015).
Generally, in wire drawing machines, the temperature rises and drawing tension are measured with thermocouples and load cell systems, accordingly, for their different speeds. It is observed that the drawing tension and temperature rise vary during the drawing process. This is undoubtedly due to the variation of the friction coefficient and material flow stress according to the drawing speed, therefore establishing a ratio between these variables (Haddi et al., 2011).

3. Methods

The research design was experimental and applied, following the initial diagnosis and a methodological process focused on the prevention of the environmental impact presented for the annealing operation through the PDCA cycle, an improvement proposal was developed. This consisted of four stages where analysis tools were applied to carry out its design, implementation, control and verification. Figure 3 below shows the stages of development of each tool described for its subsequent deployment, describing the proposal in detail.

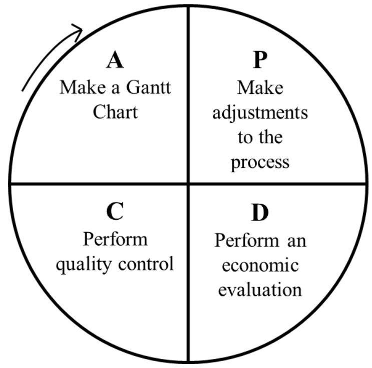

Figure 3. Stages of the study

During the Planning stage (P) it was established the goal of this proposal was oriented towards electrical power saving and responsible consumption in order to reduce the carbon footprint found. The reduction of the electrical power consumption was intended to be achieved by skipping the activity of the cathodes during the Initial annealing process. This is because the function of the cathodes is to recover the physical properties of the copper wire, which are necessary for further processing. However, it is necessary to use two drawing machines in series to obtain the required diameter. This means that the recovery of the mechanical properties of the copper wire, at the exit of the Primary drawing, is unnecessary for its entry to the secondary drawing since in this process these properties are lost. Therefore, this activity would be inefficient and would represent the misuse of electricity in the production line presented as the main problem.

At that point, the tasks to be performed for the implementation of this improvement were designated by applying a Gantt Chart.

In the second stage (D) it was intended to make two adjustments to the initial annealing process established. Image 4 shows the annealing machine, its components, the path the copper wire goes through between points 1 through 9 and cathodes A and B.

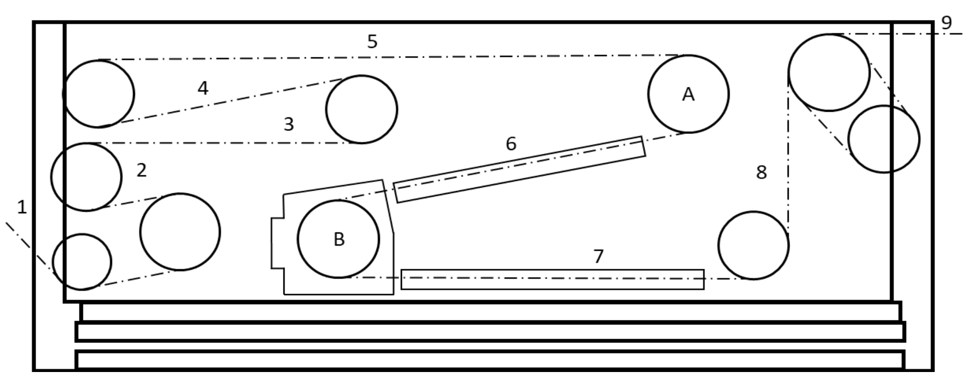

Figure 4. Sketch of the current initial annealer

According to the diagram (Figure 4), the copper wire traveled from point 1 to 5. The improvement to be designed consists of making a modification in the process, specifically in the annealing machine, so that the wire passes directly from point 1 to 7 without having to go through point 6 (between cathodes A and B), which is to be avoided. Thus, the wire will only cool down and pass-through points 8 and 9 to the next process, causing the material to be hard at the exit of the system.

The second adjustment was implemented to the two pieces of equipment called straighteners, which are systems formed by three pulleys through which the hard wire passes before being stored in the coilers. Under normal conditions, it is not necessary to adjust the machine to wind the wire, because the soft material is easily accommodated in the receiving process. However, for the hard wire that came out of the previous machine, the key was manually adjusted to bring them closer or separate them, as the case may require.

The variables cast, helix and its relation with the wire diameter were then considered to check this adjustment and make it more effective. The cast factor, defined within the welding and electrical cable industry as the diameter of the coil obtained by letting the wire coil unwind freely, was presented. It could be measured using three coils from one of the Coilers while trying not to deform them and letting them fall freely to the ground and then measuring their diameter.

Likewise, the helix factor was defined as the maximum distance between any point of the loop taken from any part and a flat surface, which can be the ground, on which the wire was supported. This factor is determined by the ratio between the cast and the diameter of the wire, thus obtaining the helix factor mentioned above by complying with the formula in Figure 5.

$$f < \frac{0.2 \cdot D}{\sqrt[4]{d}}$$

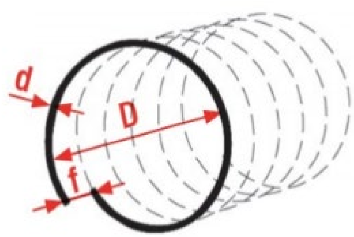

Figure 5. Cast-helix formula

In this formula, the helix factor (f) should be less than the dependence between cast (D) and wire diameter (d) in order to have a better result in the formation of the coils in the coiler, facilitating their storage.

In the third stage (C), the proposal was validated through the economic evaluation of the monthly period using the cost-benefit indicator. For the calculation of the cost-benefit, the benefit was considered as the energy-monetary savings generated by the proposal in the initial annealing. Meanwhile, the cost was composed of the total amount invested.

For the last stage (A), a quality control was performed on three 2.5 mm samples of the material taken before and after the improvements, to determine the mechanical properties of the copper wire. In order to verify that the main properties are similar among these samples and do not significantly affect the condition of the final drawn product, these tests were carried out in the laboratories of the company and the University of Lima.

3. Results

As stipulated in the methodological section, the reduction of the carbon footprint will be achieved by adjusting the initial annealing process. For planning purposes, a Gantt diagram of how the stages of the proposal is intended to be carried out is shown in Figure 6.

Activities	May									June														
	23-May	24-May	25-May	26-May	27-May	28-May	29-May	30-May	31-May	01-Jun	02-Jun	03-Jun	04-Jun	05-Jun	06-Jun	07-Jun	08-Jun	09-Jun	10-Jun	11-Jun	12-Jun	13-Jun	14-Jun	15-Jun
1st Stage																								
Improvement and factor calcullation Planning	■	■	■	■																				
2nd Stage																								
Primary wire drawing machine adjustment					■																			
Coilers' rolling machine adjustment					■																			
3rd Stage																								
Data gathering regarding the company's costs.						■	■	■																
Elaboration of the Economical Evaluation								■	■	■	■	■												
4th Stage																								
Copper wire sampling													■	■	■	■	■							
Laboratory tests																		■	■	■	■	■	■	■

Figure 6. Gantt diagram

To accomplish the first adjustment, it was proposed to avoid the initial annealing operation by passing the wire from point 1 to path point 8 without passing through the cathodes. By making this adjustment, energy savings equivalent to that spent between cathodes A and B were achieved (Figure 7).

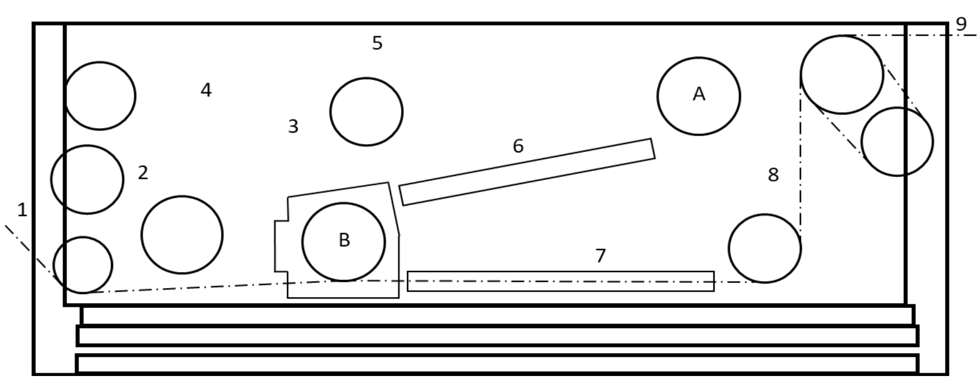

Figure 7. Sketch of the current improved annealer

Regarding the second adjustment, related to the wire winding, the helix factor was performed and calculated. Measurements were made on the hard wire and data was obtained for the two types of material that run through it. The cast was measured according to the method explained above and used in the equation presented in Table 3.

Table 3. Measuring and calculating the helix factor in millimeters

Diameter (d)	Cast (D)	Helix (f)	Final Helix
2,05	830	138,73	136
2,55	870	137,69	136

In this case, a helix of 138.73 and 137.69 millimeters was obtained for both wires of different diameters, respectively. This f-factor was rounded to the lower integer to make the adjustment to 136 mm in the straightener for both wires. This factor can be suddenly lower as this would improve the formation of the hard wire coils in the winding.
Once the adjustments were made, the economic benefit to the company was identified and calculated. The economic evaluation was used with the information of the monthly costs of the operation without including the costs that were omitted due to the improvement (Table 4).

Table 4. Annealing operation costs

Detail	(USD)
Operator's cost	688,58
Lubricant cost	3160,50
System maintenance cost	2311,00
Water consumption cost	2050,00
Preventive maintenance cost	2856,00
Total	11066,08

Likewise, the amounts that will be excluded thanks to the improvement of the process developed in the period of one month were calculated. This resulted in the economic savings shown in Table 5 and calculating the cost-benefit ratio.

Table 5. Savings from annealing operation

Detail	(USD)
Electric power cost	28766,31
Nitrogen cost	1500,00
Cost of collectors and coals	800,00
Total	31066,31
Cost-benefit ratio (Savings/costs)	2,81

With this information, the cost-benefit ratio was calculated to evaluate whether the benefits are greater than the costs or vice versa. A value of 2.81 was obtained and it can be interpreted that the benefits are greater than the costs and that the ROI for each Dollar invested is USD $ 2.81.
Finally, different tests were carried out in the laboratory for the technical validation of the proposal. Three samples of soft wire from the current process and three samples of hard wire corresponding to the improved process were taken and tested for the mechanical properties of elongation and tensile strength at break. Both groups of samples were between 2.5 to 2.6 mm in diameter and were cut to a length of 30 cm. The results are shown in the following tables (table 6 to Table 7).

Table 6. Laboratory results for soft wire

Properties	Sample 1	Sample 2	Sample 3
Diameter (mm)	2,598	2,593	2,544
Cross section (mm2)	5,301	5,281	5,083

Breaking strength (kgf)	142,85	142,41	142,21
Tensile strength at break (kgf/mm2)	26,95	26,97	27,98
Elongation (%)	35	35	36

Table 7. Laboratory results for hard wire

Properties	Sample 1	Sample 2	Sample 3
Diameter (mm)	2,604	2,601	2,552
Cross section (mm2)	5,326	5,313	5,115
Breaking strength (kgf)	240,48	240,21	240,02
Tensile strength at break (kgf/mm2)	45,16	45,21	46,92
Elongation (%)	2	2,4	2,5

Table 6 shows the results of the tests carried out on the soft copper wire samples. It shows an elongation between 35-36% and a relatively low tensile strength at break, proving that it is a soft copper wire. In turn, Table 7 shows a minimum elongation between 2-2.5% and a high tensile strength at break, proving that it is a hard copper wire. In spite of this variation in the mechanical properties of the copper wire, its use in the following processes is developed without any problem because its chemical composition does not vary and the hard material would be annealed in the second drawing and returned to its soft physical state, preserving its conductive properties.

4. Discussion

The improvement was implemented by making modifications to the annealing machine, obtaining as an economic result the cost-benefit of 2.81 USD for each Dollar invested. By having a positive indicator, it was justified that the improvement proposal could be beneficial for the company thanks to the energy savings implied by the reduction of the carbon footprint diagnosed in the initial section by mitigating 1.44 Mt of CO2eq per year.

In a study that applied cumulative energy demand modeling in an aluminum extrusion plant by adapting its improvements within the production process, it achieved a significant decrease in energy costs. It had a 10% reduction in waste from the extrusion process that could save the North American extrusion industry between 270 and 311 million dollars per year, in addition to avoiding the emission of between 0.5 and 2.3 Mt of CO2eq per year (Oberhausen et al., 2022). Thus, by making modifications or improvements within the initial annealing process, similar results to the previously mentioned cases could be achieved.

From the Technical point of view, in many cases temperature plays an important role in the drawing process. However, for this research it was not considered as a variable because if this variable was used and these values were altered, the entire drawing method and equipment would have to be changed. A modification of the model implemented by engineer Avitzur is usually presented. This model can help select the process parameters that satisfy the minimum drawing tension conditions for copper material using the temperature in a drawing machine that uses a different method (Haddi et al., 2022).

Likewise, the scope of the study could be expanded to all processes to identify their environmental impacts also with the use of the carbon footprint. This was also used in textile and metallurgy companies, among others, where different areas of the company make the necessary changes to mitigate these impacts or else, by hiring third parties to perform these tasks.

5. Conclusion

The implementation of the improvement proposal achieved the main objective of the research by reducing electricity consumption related to the company's carbon footprint during the annealing process. Furthermore, by applying industrial engineering tools in the implementation design, an economic saving was achieved, which was measured through the cost-benefit indicator, obtaining 2.81 USD, supporting the feasibility and being attractive for professionals and/or researchers who wish to replicate or improve the developed proposal.

By comparing the results obtained with those of other studies on carbon footprint reduction, the optimal economic and environmental benefits of optimizing energy use in different industries could be verified.

As a recommendation, an exhaustive study should be made of the different operations within the process to determine potential critical points in terms of energy savings. The limitation within the research is the lack of the com panies' authorities' willingness to change because the previous work method has been the easiest method to develop. However, by not analyzing in depth the environmental aspects and impacts, they are not aware that simple improvements can be made within the process that end up being beneficial in many aspects not only for a single company, but in general to many industries in the sector and the country.

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